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PHYSICAL PROPERTIES OF SYNTHETIC RESIN MATERIALS

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SUMMARY

A study was made to determine the physical properties of synthetic resins having paper, canvas, and linen reinforcements, and of laminated wood impregnated with a resin varnish.

The results show that commercial resins have moduli of elasticity that are too low for structural considerations. Nevertheless, there do exist plastics that have favorable mechanical properties and, with further development, it should be possible to produce resin products that compare favorably with the light-metal alloys.

The results obtained from tests on Compound 1840, resin-impregnated wood, show that this material can stand on its own merit by virtue of a compressive strength four times that of the natural wood. This increase in compressive strength was accomplished with an increase of density to a value slightly below three times the normal value and corrected one of the most serious defects of the natural product.

INTRODUCTION

In recent years, the use of synthetic resins in aircraft has stirred no little interest with the result that there is increased activity, both at home and abroad, in developing these materials for more varied uses in aircraft.

Because of certain advantages not found in other materials, synthetic resins are now being used for various accessories on aircraft, some of which are: cockpit enclosures, windshields, instrument dials and casings, pulleys, fair-leads, streamline housings for loop antennas, casings for lights, and cabin soundproofing.

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Synthetic resins reinforced with fibrous materials, such as cotton fabric, have demonstrated their merits with respect to being flexible, noninflammable, nonhygroscopic, noncorrosive, easily machined, and of having excellent dielectric properties. In addition, as structural materials, they have high strength-weight ratios, high energy absorption, good impact resistance, and remarkable freedom from notch sensitivity.

The mechanical advantages of these materials were realized as early as 1924, when Caldwell and Clay (reference 1) employed laminated fabric, impregnated with synthetic resin, to fabricate the first Micarta propeller. Since this pioneering work in propellers, much study has been devoted to improving the mechanical properties of resins and in the selection of more suitable reinforcing materials.

In more recent times, for an airplane designed by H. A. Atwood (reference 2), a pioneer flyer, there was used thin wood veneer impregnated with cellulose acetate, a thermoplastic resin, to fabricate by means of heat and pressure such basic parts of the plane as wings, fuselage, tail surfaces, and ailerons. This airplane was successfully flown by Clarence Chamberlin in 1935.

A relatively recent innovation, wood veneer impregnated with a resin varnish, is being employed quite extensively on the European continent in fabricating airplane propellers.

Although no attempt will be made to discuss the chemical aspects of the problem, it will be convenient for a better understanding of modern synthetic resin products to classify them according to their reaction to temperature. This classification contains two groups:

1. Thermoplastic resins.

2. Thermosetting resins.

The thermoplastic resins comprise the group of plastics that are rigid under normal temperature and stresses but deform under heat and pressure. The materials of the thermosetting group are initially in a thermoplastic state but undergo both physical and chemical changes to become infusible substances under the action of heat and pressure.

Because of the high molding temperature necessary for

the manufacture of thermoplastic resins and the instability of the resulting product at relatively low temperatures, it is obvious that these materials do not fulfill basic requirements of a structural material. Consequently, only thermosetting resins were considered in this investigation of plastics as structural materials. These are best classified in two groups:

1. Phenol-formaldehyde synthetic resins.

2. Urea-formaldehyde synthetic resins.

Both of these products are manufactured in many molded, laminated, and cast forms such as sheets, tubes, bars, rods, channels, and angles. Of these two groups, the phenol resins show a distinct advantage over the urea group which, when reinforced with a cellulose material such as cotton or wood-flour, produce brittle products. Consequently, in this investigation consideration was given only to those products having a phenol-formaldehyde bond with suitable fillers.

Pure synthetic resin alone is of no practical importance as a structural material because of its extreme brittleness. When it is combined with a suitable filler, however, a product is formed having physical properties quite unlike either of the elements from which it was fabricated. In any event, the resulting mechanical properties of a synthetic resin material are dependent upon the resin and proportions used, the filler, and lastly, the molding pressure. Insufficient molding pressure results in a brittle material of very low modulus of elasticity. By holding all other factors constant, it is possible to raise the modulus of elasticity over a wide range by increasing the molding pressure. This fact is disclosed emphatically by de Bruyne (reference 3).

MATERIALS

The plastic materials used in this investigation were commercial resins of three standard types:

1. Paper filler, laminated synthetic resin.

2. Canvas filler, coarse fabric, laminated synthetic resin.

3.   Linen filler, fine fabric, laminated synthetic resin.

Additional information was obtained from the investigation of laminated yellow poplar, impregnated with a phenol resin, and known commercially as Compound 1840. This product is not to be confused with ordinary resin-bonded plywood whose fabrication does not require the high molding pressure and heat necessary for the manufacture of Compound 1840.

The use of continuous reinforcing fillers lends itself admirably to fabrication of laminated materials. Briefly, the method of manufacture is as follows. The fabric or paper is first impregnated with a resin varnish after which it is vacuum-dried to remove all the solvents and, lastly, layers of this impregnated material are placed upon platens of a hydraulic press and subjected to a pressure of approximately 2,000 pounds per square inch and a temperature of about 300° F. for a length of time dependent, among other factors, upon the thickness of the material being fabricated. The laminated plastics are then removed and placed in a mechanical press, under small load, while cooling.

PHYSICAL PROPERTIES IN TENSION

It was stated in the Introduction that the inherent weakness of synthetic resins may be corrected by the use of proper fillers. This statement is corroborated by the results of an experimental investigation of the physical properties of synthetic resins in the pure state and with paper and fabric fillers.

A comparison of the elasticity moduli and the ultimate strengths in tension reveals several interesting facts (fig. 1).

For laminated canvas-base resin the value of Young's modulus is increased 300 percent over the value for pure resin and, in addition, the ultimate strength is increased by almost 100 percent. This improvement involved no appreciable increase in density over that of the pure resin.

The results of tension tests showed similar results for the two other materials, the value of Young's modulus for the linen-base material being 1,420,000 and for the

paper-base material being 1,600,000. Contrary to expecta-
tions, the laminated linen fabric resins did not appear
to be superior in tensile properties to the paper-base
and canvas-base materials. Since no great number of tests
were conducted on these products, however, the results
presented in this paper give the order of magnitude of
elasticity moduli that might be expected of each material
and are not to be used for precise comparisons. Slight
variations in the texture of the reinforcing material, the
resin, or the molding pressure will affect the physical
properties of the resulting product to a great extent.
But, while it is possible to vary the physical properties
of resin materials over a wide range by control of the
afore-mentioned factors, specimens from any given block of
material show uniformity of mechanical properties.

As may be seen from figure 1, the behavior of rein-
forced synthetic resins in tension is quite similar to
that of brittle materials in that the shape of the stress-
strain diagram of the plastic product deviates from a
straight line at very low stresses, 2,000 to 5,000 pounds
per square inch. The original test data indicate that, if
the stress-strain curves were plotted on a larger scale,
little or no semblance of a linear portion would be notice-
able.

The selection of a continuous tension reinforcing ma-
terial for synthetic resins is made from those products
having properties of elongation similar to that of the
resin material. Consequently, the resin and its reinforce-
ment act together at stresses below the ultimate stress of
the resin. Above this value the resin begins to separate
from its reinforcement and the full load is then carried
only by the reinforcing material. Observation of the be-
havior of reinforced synthetic resins in tension bears out
the contention, for surface cracks were to be seen on the
specimens shortly before failure occurred.

By contrast, the behavior of Compound 1840 shows a
stress-strain relation that deviates from a straight line
only at high stress. From figure 2, the proportional lim-
it appears to vary from 10,000 to 24,000 pounds per square
inch, with failure of the material occurring at about 30,000
pounds per square inch. The modulus in tension for this
material, 3,500,000 pounds per square inch, is appreciably
higher than that of the reinforced synthetic resins: nat-
ural wood, yellow poplar, 1,300,000 pounds per square inch,
or of plywood made of poplar lamina, 1,500,000 pounds per
square inch. As may be noticed from this same diagram, a

wide range of modulus was obtained although the test spec-
imens were cut from the same block. A greater degree of
uniformity could be obtained were thinner lamina of wood
employed in the fabrication of this material, for then
deeper and more uniform penetration would result. Other
tension tests, whose results have not been plotted in fig-
ure 2, indicate for this material a modulus of 3,500,000
pounds per square inch whereas the modulus of curve 2
(4,500,000 pounds per square inch) is obtained occasion-
ally from tension tests and also from tests in bending.
(See fig. 5(b).)

The nature of failure of this resin material is not
unlike that of the natural wood, in that failure occurs
suddenly leaving serrated fibers at the point of fracture.
The nature of fracture depends to a great extent upon the
shape of the specimen. Flat rectangular sections fail
with large jagged edges, owing to initial shearing at the
surfaces of lamination. Large specimens, either round or
rectangular, fail cleanly in the plane of normal stress.

PHYSICAL PROPERTIES IN COMPRESSION

The behavior of synthetic resins in compression when
reinforced by a continuous filler is similar to that of a
ductile material. The stress-strain curve is linear up to
stresses of 4,000 to 5,000 pounds per square inch. Be-
yond this value the strain increases rapidly for small in-
crements of stress. (See fig. 3.) Although the shape of
the stress-strain diagram is considerably altered by the
use of a reinforcing material, the ultimate strength in
compression is not affected appreciably; it is of a magni-
tude comparable with that of the unfilled resins. This
result is logical because the type of continuous reinforce-
ment used cannot withstand compression loads. The resin
acts as a stabilizing medium for the fabric when in com-
pression. The reinforcement, in turn, restrains the resin
from developing rapid crack formations due to brittleness,
as would occur in the unfilled resin. The general behav-
ior of reinforced resin points to a possible relationship
between the molding pressure and the stress at which the
stabilizing effect of the resin ceases and plastic deforma-
tion begins. If the value of stress on the compression
stress-strain diagram is therefore taken where the curve
rapidly deviates from the linear portion, which is approxi-
mately 6,000 pounds per square inch, and a Poisson's ratio

of 0.30, this value will then corespond to a lateral
stress of 2,000 pounds per square inch, the order of pres-
sure employed in molding the resin materials (reference 3).

In order to determine the behavior of synthetic res-
ins under repeated loading, tests were conducted on a rod
of this material having a linen reinforcement. The re-
sults, as may be seen in figure 4, indicate typical "hys-
teresis" effects, a small hysteresis loop when the unload-
ing occurred at a low stress, and a larger loop when the
stress at the point of unloading is raised. The action of
synthetic resins under repeated loading at low stress is a
true "elastic" hysteresis effect (reference 3) and differs
from plastic hysteresis of metallic materials. This dif-
ference may be noted in the similarity of slopes of each
reloading curve (fig. 4) with that of the initial loading
curve and, too, in the approach of the reloading curve to
approximately the same value of strain at each value of
stress where unloading occurred.

This hysteresis effect at low stress is probably the
most serious drawback to the use of synthetic resins as a
structural material because of the difficulties that would
be encountered from permanent deformation in a structure
as the result of applied loads.

Compound 1840 in compression (fig. 3) exhibits ex-
tremely favorable characteristics with both the modulus of
elasticity and the ultimate strength approaching quite
closely the values obtained from tension tests. The abil-
ity of this material to withstand compressive stresses some
four times as great as the natural wood, i.e., 21,000 com-
pared with 5,000 pounds per square inch, with an increase
in density of less than three times, is especially grati-
fying.

The manner of failure of this material depends, as
in tension, upon the cross-sectional shape and the length
of the specimen. Slender columns first show signs of sur-
face cracks on the tension side of the buckled column,
penetrating deeper as the load is increased, until a sur-
face between adjacent laminations is reached that is too
weak to resist the lateral stress, thus causing the spec-
imen to fail along the lamination. Short columns behave
differently in that they fail, invariably, by shear along
the axis of principal stress.

FLEXURE

Because of the nonlinear stress-strain relation found even at low stress in reinforced synthetic resins, the ordinary relations $f_b = My/I$ and $1/\rho = M/EI$, are not applicable. Some idea of the divergence between the true maximum normal stress on a cross section and that computed by the formula $f_b = My/I$ may be obtained from the results of a test in pure bending plotted in figure 5(a). In this test a beam of rectangular cross section was simply supported and subjected to equal symmetrically located loads near the points of support so that the portion between the loads was subjected to pure bending of known magnitude. During the test the strains of the extreme fibers were measured by Huggenberger tensiometers. The values of strain thus observed were assumed to correspond to the stresses that produced the same strains in previous direct tension and compression tests of this material. In this manner the necessary data were available for plotting the bending moment-stress diagram of figure 5(a), which shows both the observed unit stresses and those computed from the usual formula. In this figure it will be noted that the observed true stresses are greater than the computed stresses for the fibers in tension but approximately the same for those in compression.

The relationship shown in figure 5(a) is purely empirical and would be of little use in predicting the maximum unit stress resulting from the bending of a reinforced synthetic resin beam of a different shape or different chemical composition. Although a general method of computing the maximum normal stress on a cross section of a synthetic resin beam with a nonlinear relation of stress to strain has not been developed, C. V. Bach has proposed (reference 4), for the case of a rectangular section subjected to pure bending, a special method based on the relation:

$$(2M + \theta \, dM/d\theta) = bh^2 \, (s_1 \, s_2/s_1 + s_2) \qquad (1)$$

where

M is the bending moment.

θ, $(\epsilon_1 + \epsilon_2) L/2h$ = change of slope in $L/2$.

b, width of beam.

h,   depth of beam.

s_1 and s_2,   stresses on extreme fibers.

ϵ_1 and ϵ_2,   strain of extreme fibers.

The left side of equation (1) may be evaluated if the strains of the extreme fibers are observed during a bending test. With this information available, a curve of the relation between M and θ may be plotted, and the value of dM/dθ will be the tangent to the curve of $M = f(\theta)$ at the bending moment M, for which the values of s_1 and s_2 are desired. (See fig. 6.)

In order to evaluate the right side of the equation, it is first necessary to establish the ratio of s_1/s_2. This evaluation may be accomplished by plotting a curve of the observed values of M against ϵ_1 and ϵ_2 from which the ratio $d\epsilon_2/d\epsilon_1$ may be obtained, since $d\epsilon_2/d\epsilon_1 = dM/d\epsilon_1 \times d\epsilon_2/dM$. (See fig. 7.) For a condition of equilibrium of stresses at any cross section of a beam subjected to bending, $s_1 d\epsilon_1 = s_2 d\epsilon_2$, then it follows that $s_1/s_2 = d\epsilon_2/d\epsilon_1$.

The foregoing ratios, s_1/s_2, dM/dθ, and $d\epsilon_2/d\epsilon_1$ correspond to but one value of bending moment M for which s_1 and s_2 are desired. New ratios must be obtained for other values of M.

Although the practical value of the Bach method is debatable, it does nevertheless present a means of obtaining the normal maximum stress in beams of synthetic resins without resorting to the results of stress-strain diagrams from tests in direct tension and compression.

It is interesting to note that the observed stresses of figure 5(a) agree closely with those computed by the Bach procedure, thus indicating that data from stress-strain curves obtained in tests under axial loads are applicable to computations of unit stresses produced by bending, and vice versa.

Inasmuch as Compound 1840 shows a true elastic behavior, the ordinary relation between bending moment, slope, and stress may be employed. For flexure tests 2 and 3

(figure 5(b)) stresses were calculated by the conventional
equation, $f_b = My/I$, and these values were plotted
against strain-gage readings. The modulus of elasticity
in tension obtained from flexure test 2, in which the loads
were applied perpendicular to the laminations, corresponds
closely to the lower values shown in figure 2; whereas that
of test 3, load parallel to laminations, yielded a modulus
of elasticity of the higher order, 4,200,000 pounds per
square inch, previously mentioned in Physical Properties
in Tension. This fact, in itself, upholds the possibility
of a wide variation in physical properties of this product.

FATIGUE CHARACTERISTICS

Static Endurance

Tests of static endurance were conducted only on Com-
pound 1840.

As may be seen from figure 8, the ability of this ma-
terial to carry large loads for short periods is greater
than for smaller loads applied over a long time. From
this same graph, the results appear to indicate a static
fatigue limit of about 55 percent of the instantaneous ul-
timate load.

The results of this investigation are based upon loads
applied both perpendicular to and parallel to the lamina-
tions. The similarity of both results justifies the use
of but one curve to define the relation between fiber
stress and time to fracture.

Dynamic Endurance

Only Compound 1840 was investigated for dynamic endur-
ance and the results of the tests are expressed graphic-
ally in figure 9.

The behavior of Compound 1840 in rotating-beam tests
is quite different from the action of metallic materials.
Because of the fibrous character of this product, sudden
failure does not occur and a specimen may continue to hold
together for thousands of cycles after the formation of a
peripheral crack. This effect was noted in several tests.

The results of this investigation indicate a dynamic-fatigue limit of about 21 percent of the static bending stress. Dynamic-endurance tests on synthetic resins conducted elsewhere (reference 5) indicate a fatigue limit for these materials ranging from 35 to 65 percent of the static tensile stress. All dynamic-endurance tests were conducted on a Wohler-type Tinius Olsen rotating-beam machine.

ENERGY ABSORPTION

Of the various methods for determining the internal damping of a material, the method of free torsional oscillation is perhaps the simplest and most accurate (reference 6). For any material, the internal damping is a function only of the internal characteristics of the specimen, and independent therefore of its length and cross-sectional area, provided the amplitudes of oscillation are not large enough to produce plastic deformation (reference 3).

The equipment shown in figure 10 was employed to obtain the internal damping characteristics of a strip of synthetic resin by the free torsional oscillation method. By means of the telescopic arrangement, it was possible to read successive amplitudes of the bobweight attached to the specimen. Several tests at different periods, namely, 1, 1.5, and 1.8 seconds per oscillation, were investigated. For oscillations of small amplitude the energy absorbed may be expressed (reference 7) as:

$$\psi = 2 \log_e (X_n/X_{n+1})$$

where ψ is the percentage of strain energy absorbed.

X_n, the amplitude of one swing.

X_{n+1}, the slightly reduced amplitude of the next swing.

Using this procedure for the three different periods of oscillation just mentioned, the energy absorbed by a strip of linen-base synthetic resin 1/16 inch thick was found to be 22 percent. This result neglects the small damping due to air resistance of the bobweights. (See fig. 10.) Similar tests on metallic materials, using more accurate equipment, have been made by Iobike and Sakai;

their results are given in the following table (from reference 7).

Material	Energy absorbed (percent)
Zinc	11.70
Aluminum	1.10
0.55 percent carbon steel	.24
0.99 percent carbon steel	.17
Nickel	.021

NOTCH SENSITIVITY

The behavior of notched resin specimens, fabric reinforcement, in tension exhibit an apparent increase in tensile strength. This same phenomenon is present in ductile materials; the explanation being that the notched portion is prevented from contracting laterally (necking) by the adjacent unnotched material (reference 8). Figure 11 shows the apparent variation in tensile strength for only four tests of specimens having varying ratios of b/B.

Inspection of the notched specimens after each test revealed interesting slip lines on both sides of the plane of fracture. Photomicrographs (×6.3) were made of these specimens, one of which is presented (fig. 12). The slip lines are clearly visible as cracks on the surface of the resin just above and below the plane of fracture. The threads of the fabric appear white upon the black background of the resin.

BOLTS IN BEARING

Results of tests on synthetic resins and Compound 1840 in bearing are given in figure 13. In general, Compound 1840 appears to be better than the resin material, except when the comparison is made for loads applied perpendicular to the grain of the wood product. Because of the weakness of wood in shear and tension across the grain, failure of Compound 1840 occurred by shear when the load was applied in the direction of the grain and by tension when the load was applied perpendicular to the grain. These results indicate that some of the inherent disadvantages of natural wood have not been removed in the fabri-

cation of Compound 1840 and that it is still necessary to use transverse grain in making laminated-wood materials.

The nature of failure of the resin material is best shown by a photomicrograph taken of one of the specimens tested. Slip lines acting along the trajectories of principal stress are clearly visible in figure 14. The two heavy white bands show complete failure of the resin and the reinforcing fabric, starting at right angles to the tangent to the periphery at that point, then dropping downward sharply in the direction of the applied load. Other cracks in the resin, emanating from the bolt hole, indicate separation of the resin from the fabric.

CORROSION RESISTANCE

Corrosion tests were carried out on Compound 1840, and on synthetic resins having paper, canvas, and linen reinforcements. Inspection of these materials after being immersed in "high-test" gasoline, motor oil, and brine for a period of 1 month showed no deleterious effects.

DISCUSSION

From the foregoing investigation, and from the results of similar studies at other laboratories, one finds that only the laminated synthetic resins need be considered. The average values of the physical properties of these resins are compared with Compound 1840 and other aircraft materials in table I.

The foregoing comparisons show that the moduli of elasticity of the laminated products tested are too low to be useful as structural materials in aircraft. This statement covers only our present commercial resins, which, it must be understood, were manufactured primarily for electrical purposes and it does not mean to imply that the synthetic resins have no future as structural materials for aircraft. Although the author was not fortunate enough to obtain such specimens, there are nevertheless reinforced resin products now on the commercial market that have moduli of elasticity of approximately 2,500,000 pounds per square inch. The results of recent experiments abroad, notably those of de Bruyne (reference 3), have re-

vealed new synthetic resin materials having about three times the modulus of our present resin products and from one-third to one-half that of our light alloys, with no appreciable increase in density. Similar interesting results have been obtained also in the laboratories of Germany (reference 5), where intensive study of reinforced synthetic resins are now in progress.

Coordinated research to develop a reinforcing material different from those which are now being used will be necessary to raise the modulus of elasticity and with it the tensile strength of future reinforced resins. Until such time as a reinforced resin product can be developed having isotropic characteristics, one can employ tension reinforcements to act in the direction of maximum stress, thus enabling the material to operate at maximum efficiency.

The properties of the present plastic products are quite favorable in compression and have excellent qualities in bearing. With continued investigation of the problem even these properties may be improved.

The flexibility of resin materials makes it possible to fabricate complete units, such as fin, rudder, stabilizer, as an initial venture in the use of plastics in aircraft.

Comparison of synthetic resins with metallic materials on the basis of the ratio of strength or modulus to specific gravity may put these materials in an unfavorable light. The comparison is too general and does not take into account the geometry of the structure. In this respect, evaluating the stiffness of a stressed-skin structure, the ratio of strength to specific gravity, σ/γ is of no significance but rather the ratio $\dfrac{\sqrt[3]{E}}{\gamma}$, where E is the modulus of elasticity and γ, the specific weight. This comparison is the more logical one and places the synthetic-resin materials in a more favorable position. This fact can be emphasized further by a simple problem.

Rectangular isotropic plates, simply supported and loaded on one pair of edges (reference 9).

$$\sigma_{cr} = K \frac{E}{(1 - \mu^2)} \left(\frac{t}{b}\right)^2$$

then for equal values of σ_{cr} and aspect ratio but different thickness, t:

$$E_1 t_1^3 = E_2 t_2^3$$

the ratio of weights is therefore:

$$\frac{W_1}{W_2} = \left(\frac{\gamma_1}{\gamma_2}\right)\left(\frac{E_2}{E_1}\right)^{1/3}$$

where

σ_{cr} is critical stress.

E, modulus of elasticity.

K, nondimensional factor.

μ, Poisson's ratio.

t, thickness of plate.

b, width of plate.

W, weight of plate.

γ, specific gravity.

Comparing linen-reinforced laminated synthetic resin with 24ST aluminum alloy:

Resin   1.30 $E_1 = 1.43 \times 10^6$ lb./sq.in.

24ST aluminum alloy   2.76, $E_2 = 10.4 \times 10^6$ lb./sq.in.

therefore, $W_1 = 0.915 W_2$. The weight of the resin plate is thus slightly less than that of the aluminum.

By similar reasoning, for the problem of a rectangular strut of constant width in compression, the same result is obtained, namely, $W_1 = 0.915 W_2$.

Another interesting property of the synthetic resin materials is their large damping capacity. This physical property is desirable in aircraft structures where, owing to aerodynamic forces, wings and especially tail surfaces

are subjected to undesirable vibrations. The internal damping of these materials would tend to suppress the amplitudes at critical speed, thus minimizing the possibility of a structural failure. Although it is a desirable quality, an excess of damping would be disadvantageous because of the heating caused by internal friction. By way of comparison, the internal damping of synthetic resin materials is 20 times as great as that of aluminum.

Compound 1840 holds a more favorable position as a structural material, as may be seen from table I. This product compares favorably with aluminum alloy and Dow-metal on the basis of the ratio of elasticity to specific gravity. On the basis of ultimate strength to specific gravity, it is actually better than aluminum alloy. When comparisons were made of this material and aluminum alloy acting as a rectangular plate and as a beam in compression, it was found that Compound 1840 was superior to aluminum alloy in each case. For the rectangular plate in compression, Compound 1840 was 30 percent lighter than aluminum alloy and, as a beam, it was 25 percent lighter. Both comparisons were made on the basis of equal strength.

The improvement that has been made in the compressive strength of this material over the natural wood will give products of this sort added prestige in the aircraft industry. With the introduction of resin-impregnated wood on the commercial market, varied applications of this product in aircraft structures will undoubtedly be found, such as wing beams, flooring, empennage, etc.

CONCLUSIONS

The future of plastics and wood impregnated with resins depends to a great extent upon the impetus which the aircraft industry, in cooperation with the manufacturers of these products, is willing to give to experiments and to the development of these materials from considerations of improved mechanical strength. For plastics to be active competitors of the present light alloys, they must be improved to the point where they have well-defined physical properties and, in the case of wood, the heterogeneous character of the material must be changed to one that approaches homogeneity.

It is realized, at present, that the use of synthetic

resin materials in the aircraft industry have been limit-
ed to miscellaneous accessories. The future is promising,
however, for with continued development, resin materials
suitable for aircraft structures will be produced. Those
plastic products must incorporate the present low density,
smoothness of surface, and flexibility, in addition to an
increased elastic modulus and with it greater design pos-
sibilities.

New encouragement for the future of plastics in air-
craft comes from a recent report of the development of
molded plastic aircraft by the United States Army in con-
junction with several aircraft companies.

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TABLE I - COMPARISON OF AVERAGE PHYSICAL PROPERTIES OF REINFORCED SYNTHETIC RESINS AND COMPOUND 1840

WITH VARIOUS AIRCRAFT MATERIALS

[Flatwise: Designates loads applied perpendicularly to laminations.

Edgewise: Designates load applied parallel to laminations in direction of greatest strength.]

Material	Tensile strength, (lb./sq. in.)	Modulus E (lb./sq.in.)	Compression strength, column (lb./sq. in.)	Modulus E (lb./sq.in.)	Compression strength, block (lb./sq.in.)		Shear strength (lb./sq.in.)	
					Flatwise	Edgewise	Flatwise	Edgewise
Synthetic resins:								
Paper	15,325	1,610,000	21,725	1,575,000	42,000	26,800	8,725	8,550
Canvas	10,200	1,800,000	18,350	1,100,000	45,000	29,275	10,000	10,175
Linen	10,000	1,430,000	19,550	1,900,000	51,600	27,900	10,900	11,530
Compound 1840	29,650	3,500,000	21,205	3,175,000	18,010	24,925	5,320	4,100
[1]Aluminum alloy, 24ST	62,000	10,400,000	40,000	10,400,000	40,000	40,000	40,000	40,000
[2]Dow metal, M	40,000	6,500,000	46,000	6,500,000	60,000	60,000	18,000	18,000
[3]Aircraft spruce	10,000	1,300,000	5,000	1,300,000	840	5,000	750	-

Material	σ_t/γ (in.-lb. units)	σ_c/γ (in.-lb. units)	E/γ (in.-lb. units)	$\sqrt[3]{E}/\gamma$ (in.-lb. units)	Rockwell-B (hardness)	Specific gravity	Water absorbed in 24 hours (percent)
Synthetic resins:							
Paper	11,200	15,540	1,178,000	86	20	1.37	0.90
Canvas	7,850	14,110	1,386,000	94	25	1.30	.42
Linen	7,700	15,020	1,100,000	87	30	1.30	.24
Compound 1840	23,520	16,870	2,780,000	121	-	1.26	6.24
[1]Aluminum alloy, 24ST	22,500	14,500	3,770,000	79	-	2.76	-
[2]Dow metal, M	21,900	25,150	3,550,000	102	30 - 51	1.83	-
[3]Aircraft spruce	25,000	12,500	3,250,000	273	-	.40	-

[1] Manufacturer's data: pamphlet of Aluminum Corporation of America.

[2] Manufacturer's data: pamphlet of Dow Chemical Corporation.

[3] Niles, A. S., and Newell, J. S.: Airplane Structures. John Wiley & Sons, Inc., 1929, p. 377.
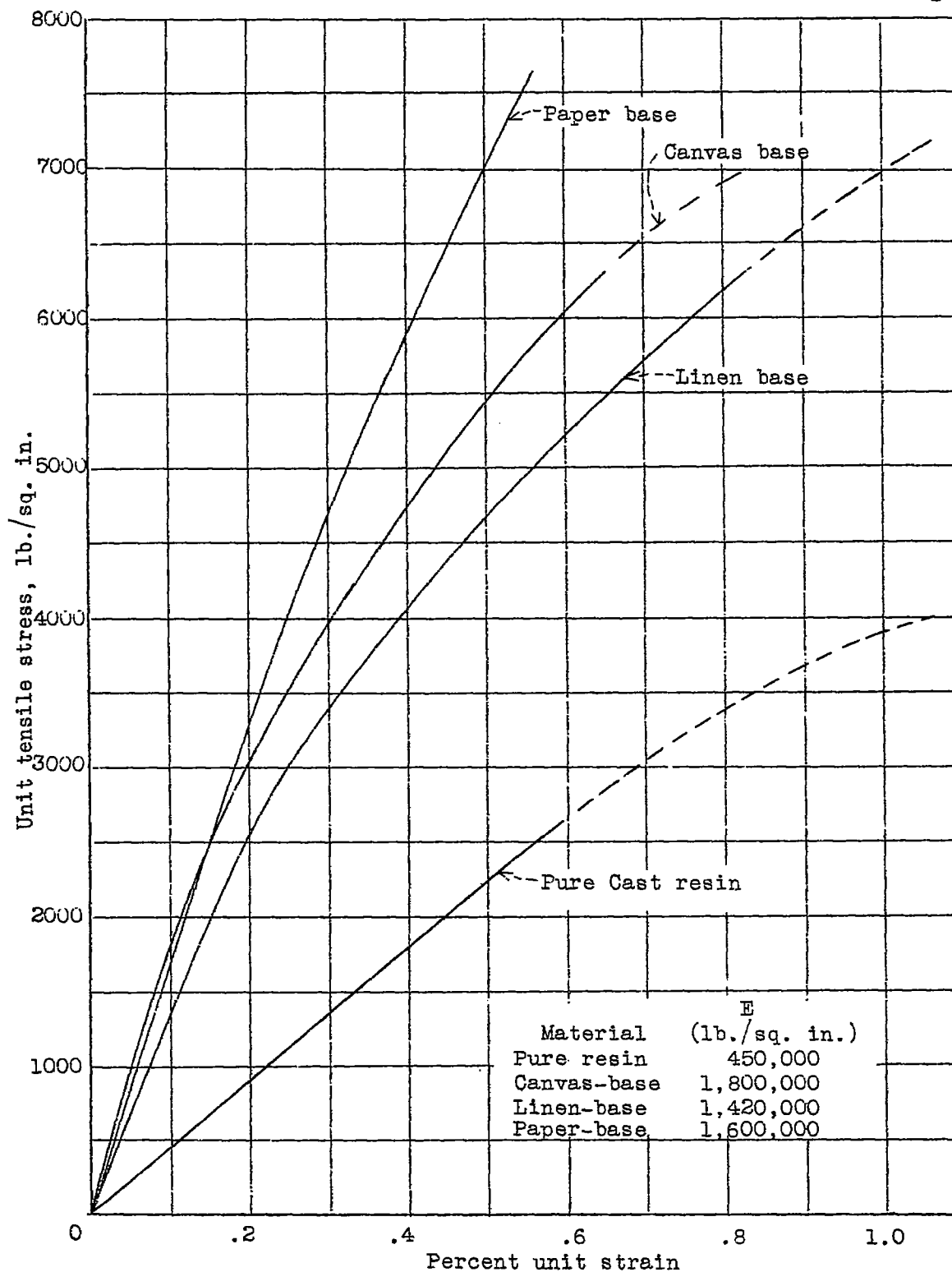
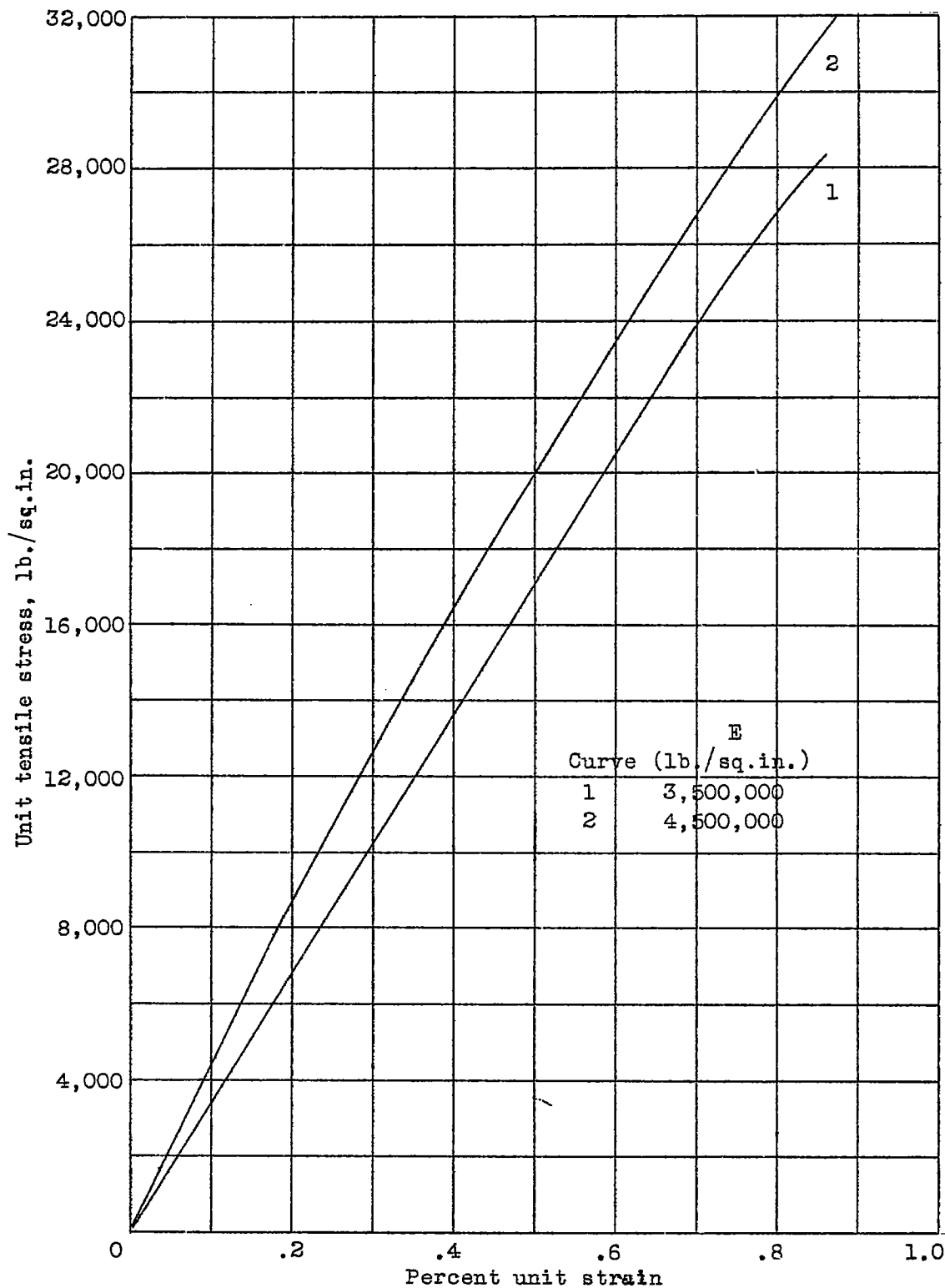Table 1

Figure 1.- Synthetic resin in tension.
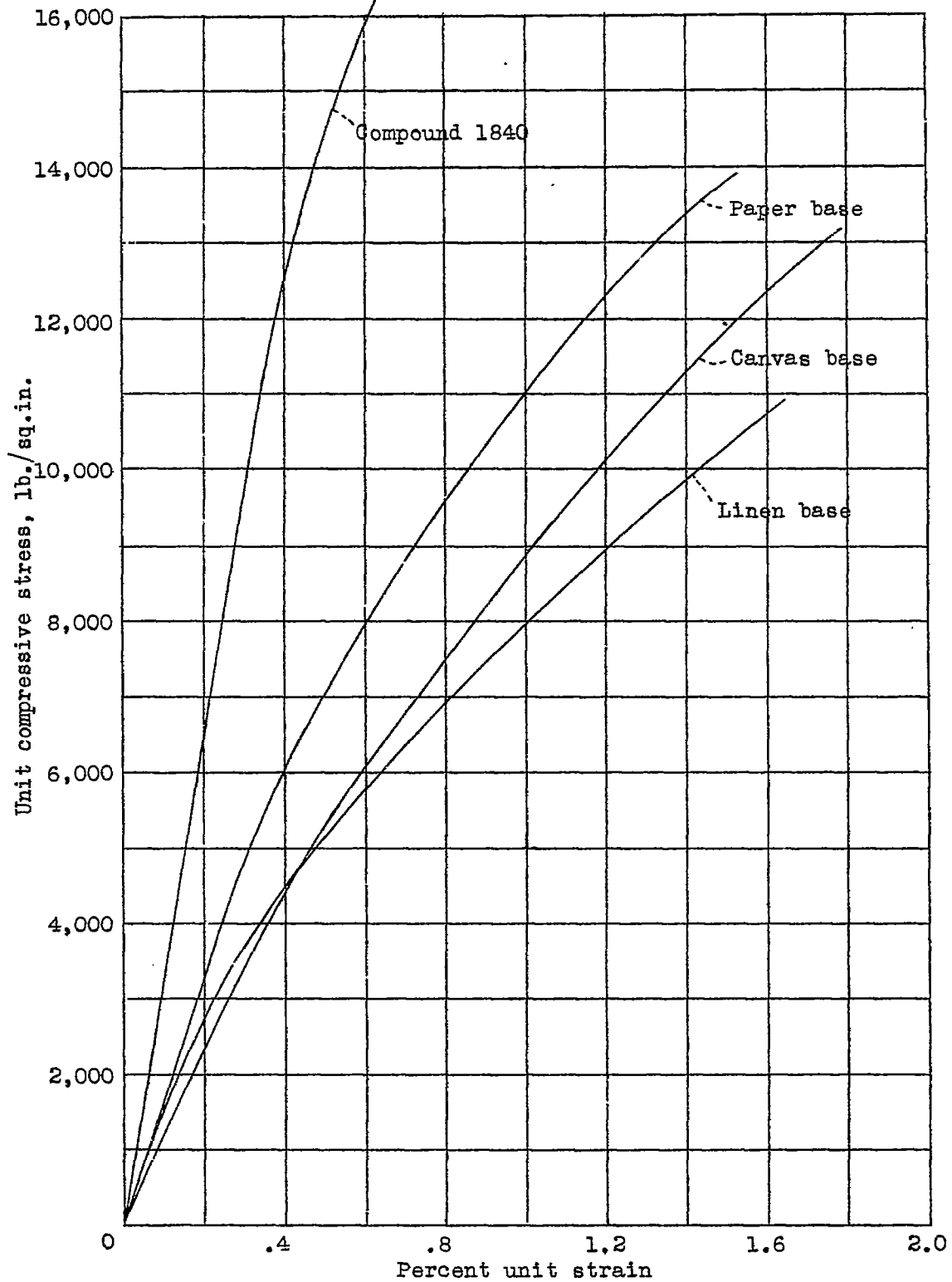
Figure 2.- Compound 1840 in tension.

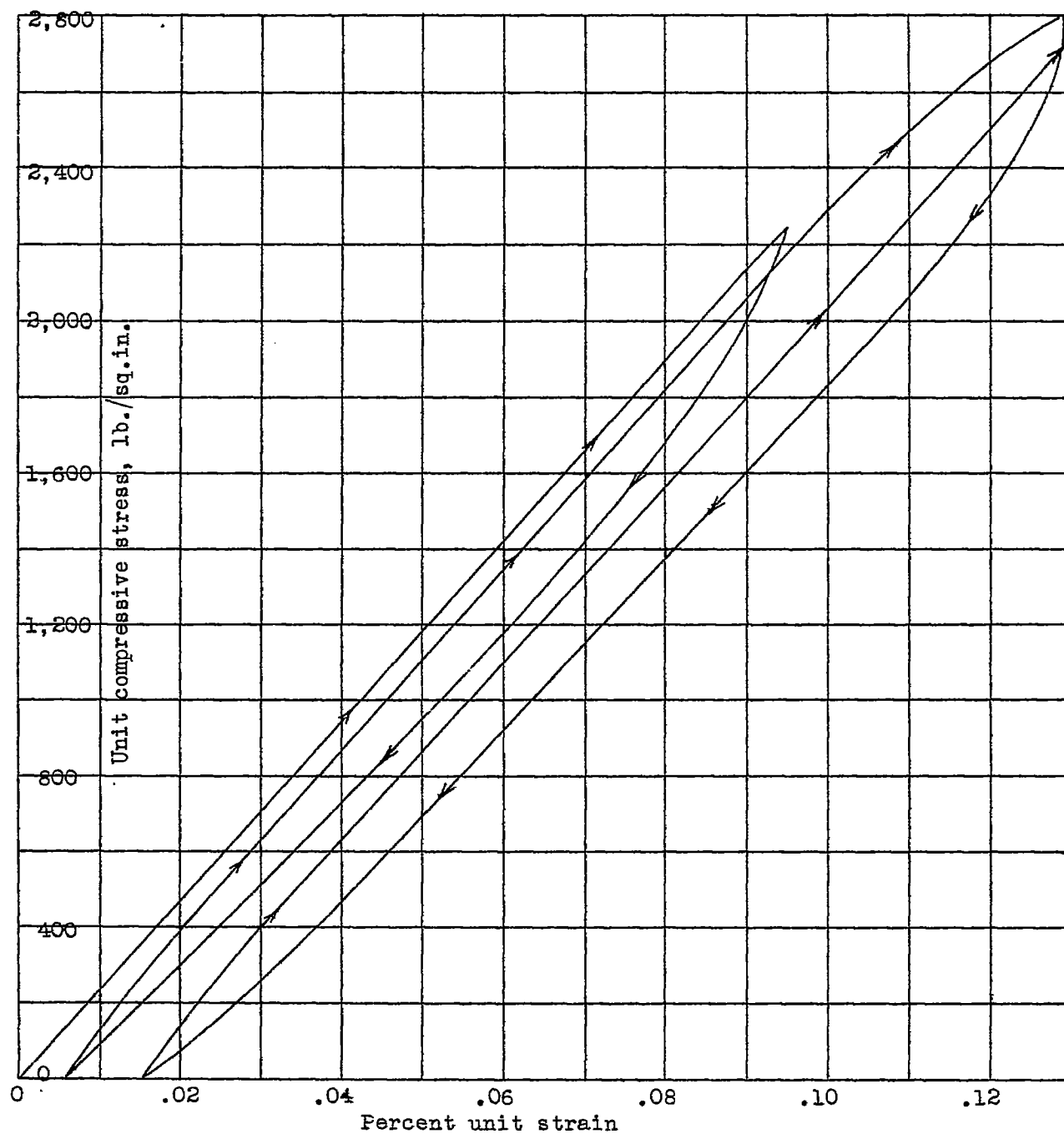Figure 3.- Properties in compression.

Figure 4.- Repeated loading in compression on a rod of synthetic resin with linen base.
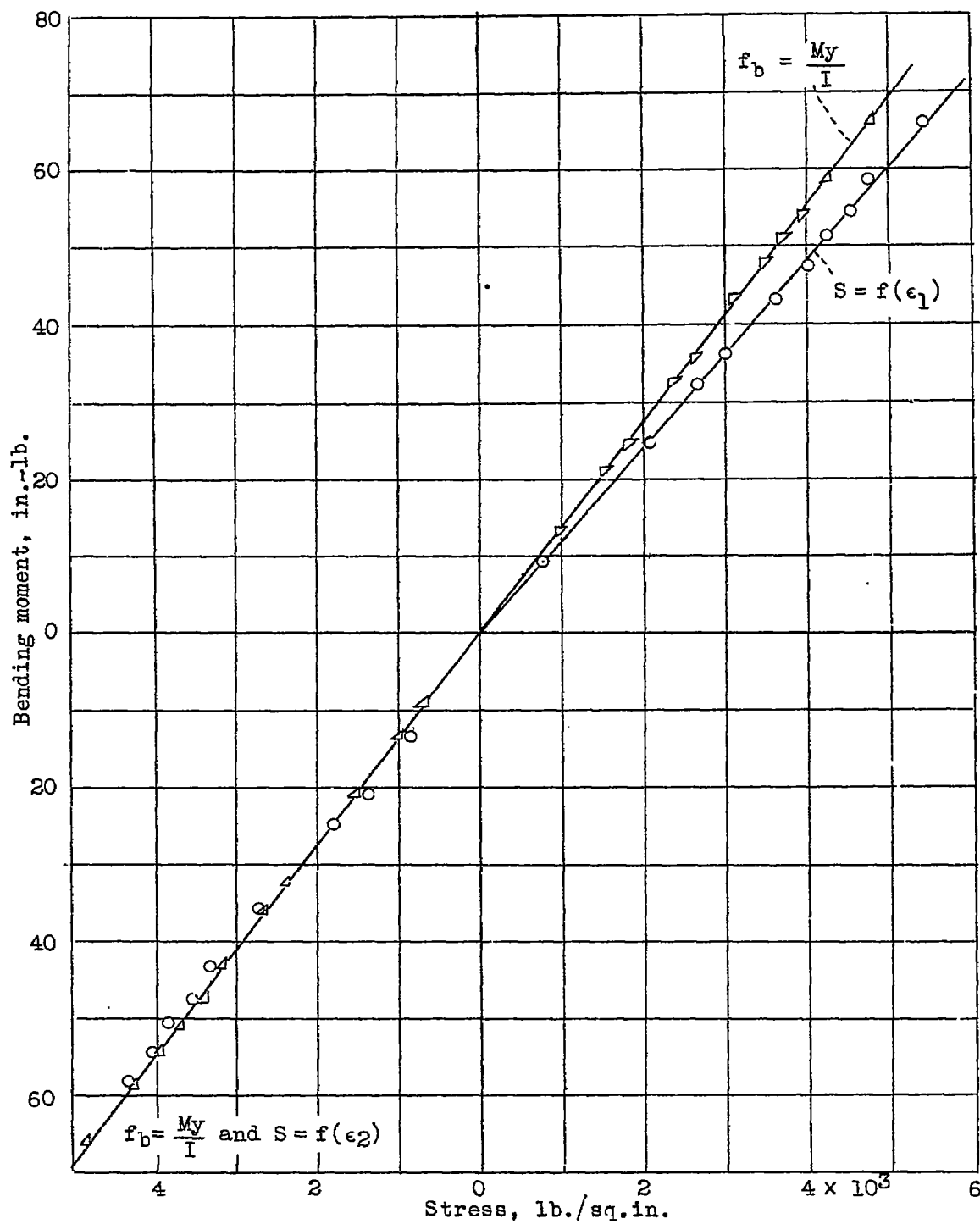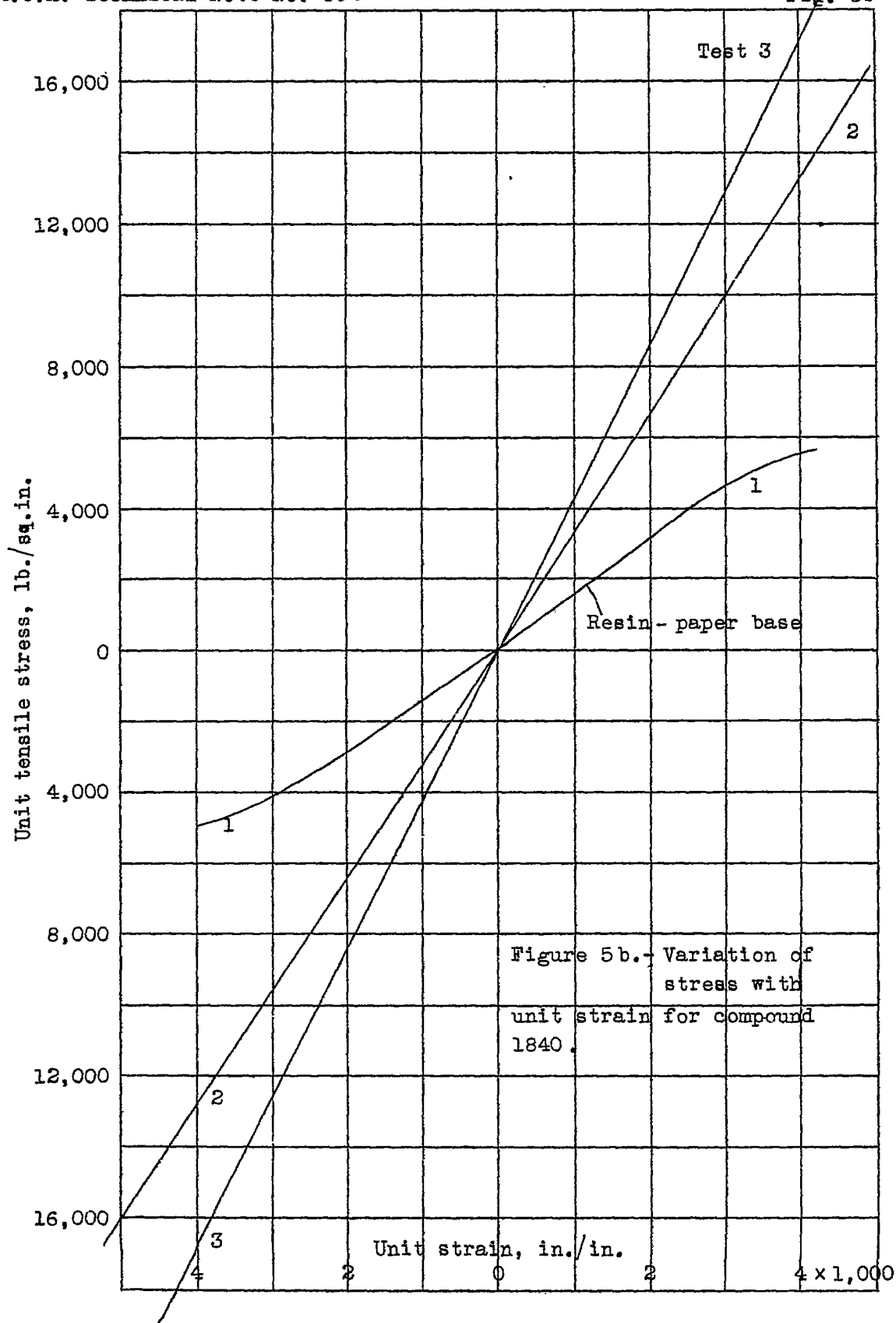
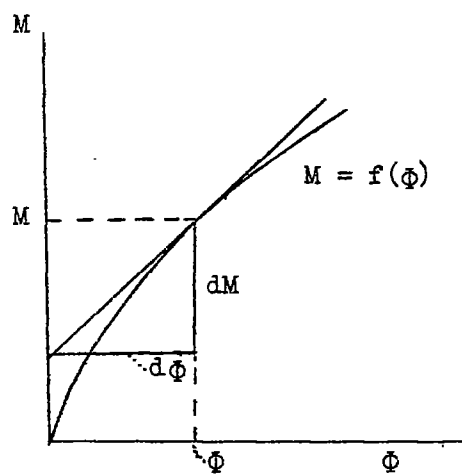Figure 5a.- Variation of stress with bending moment for synthetic
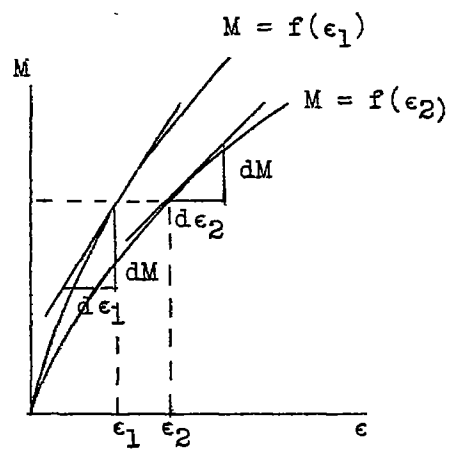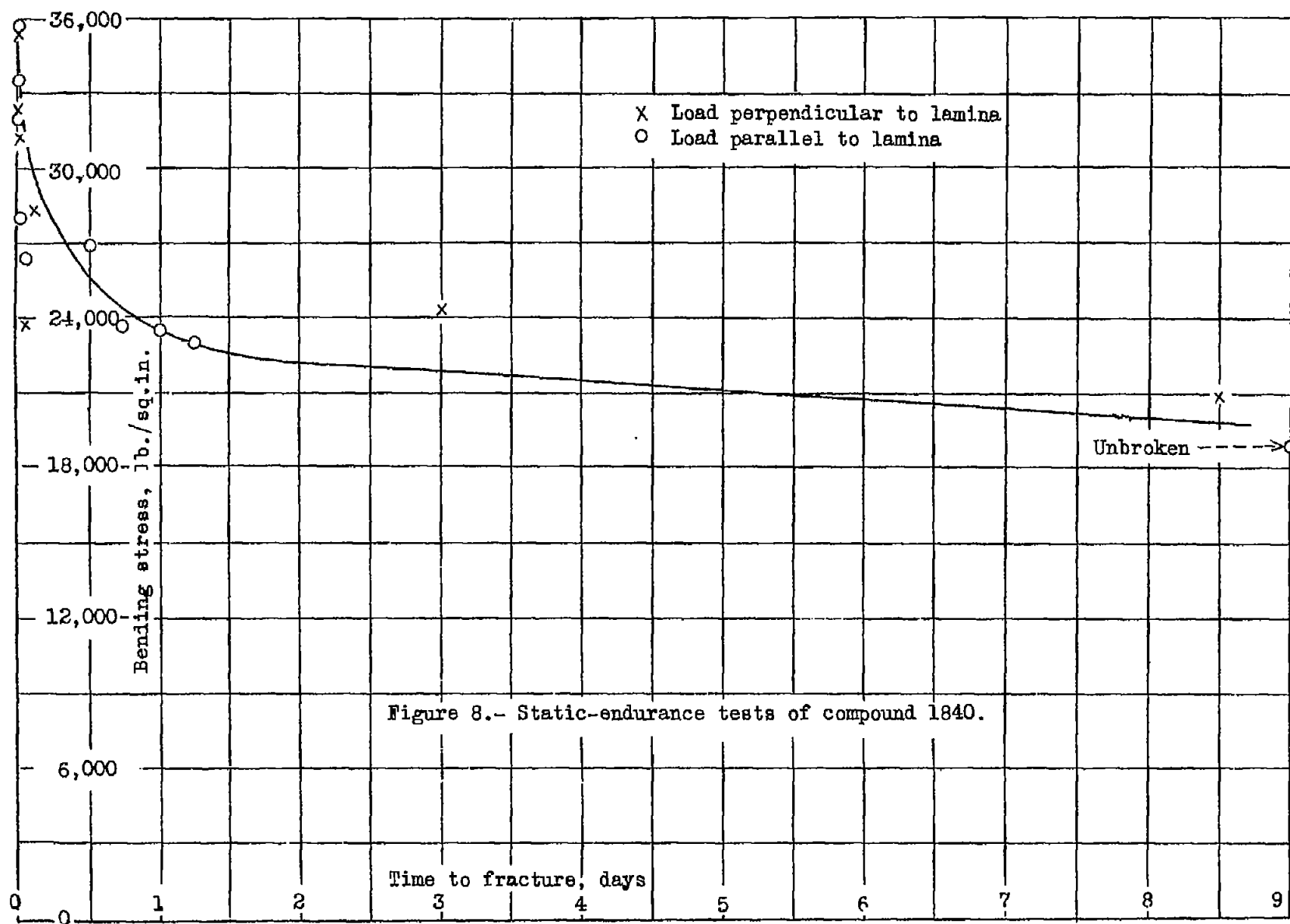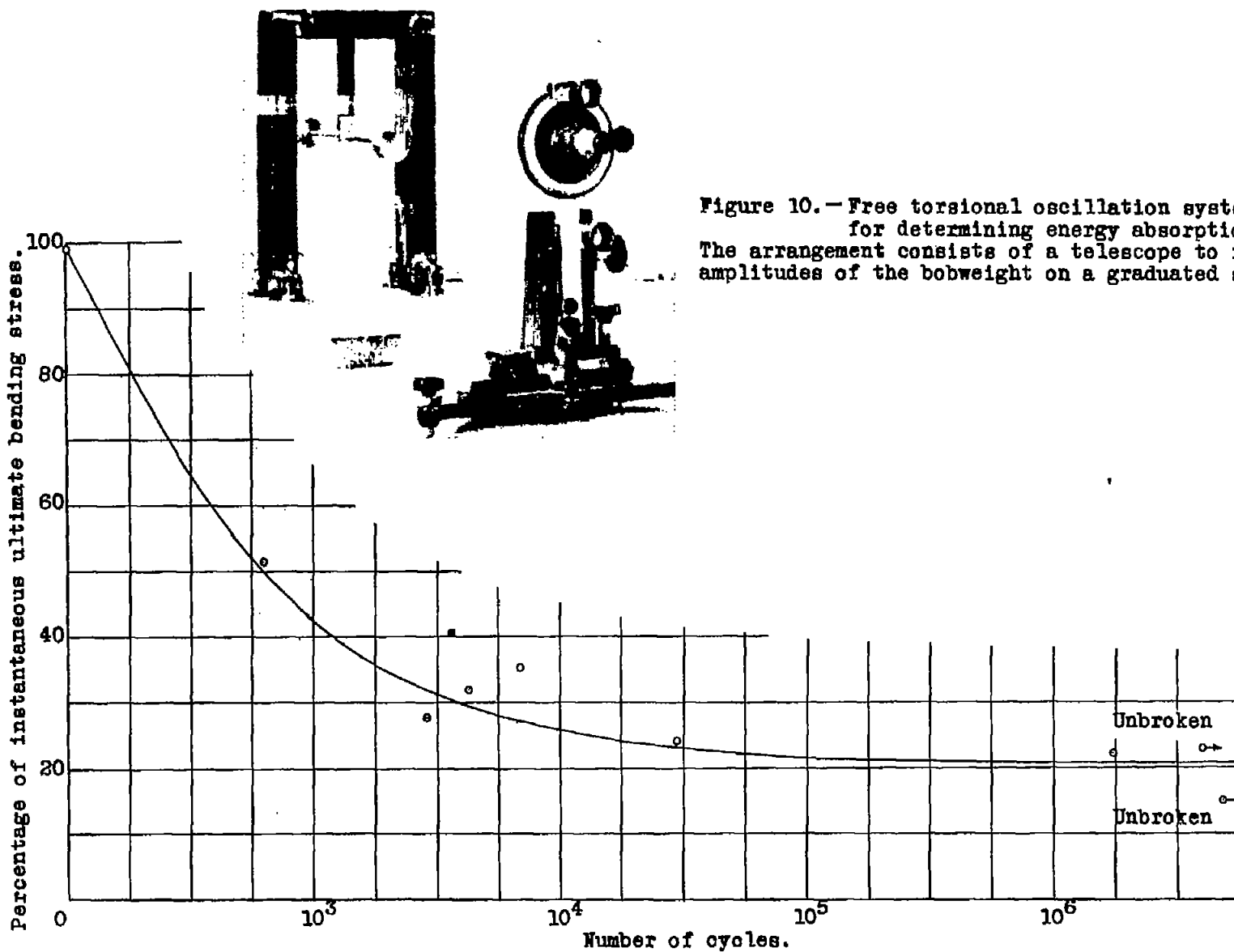resin, paper base.

Figure 5b.- Variation of stress with unit strain for compound 1840.

Figure 6

Figure 7

Fig. 8

X   Load perpendicular to lamina
O   Load parallel to lamina

Unbroken -----→O

Bending stress, lb./sq.in.

Time to fracture, days

Figure 8.- Static-endurance tests of compound 1840.

Figure 10.— Free torsional oscillation system
for determining energy absorption.
The arrangement consists of a telescope to read
amplitudes of the bobweight on a graduated scale.

Figure 9.— Dynamic-endurance tests of compound 1840.
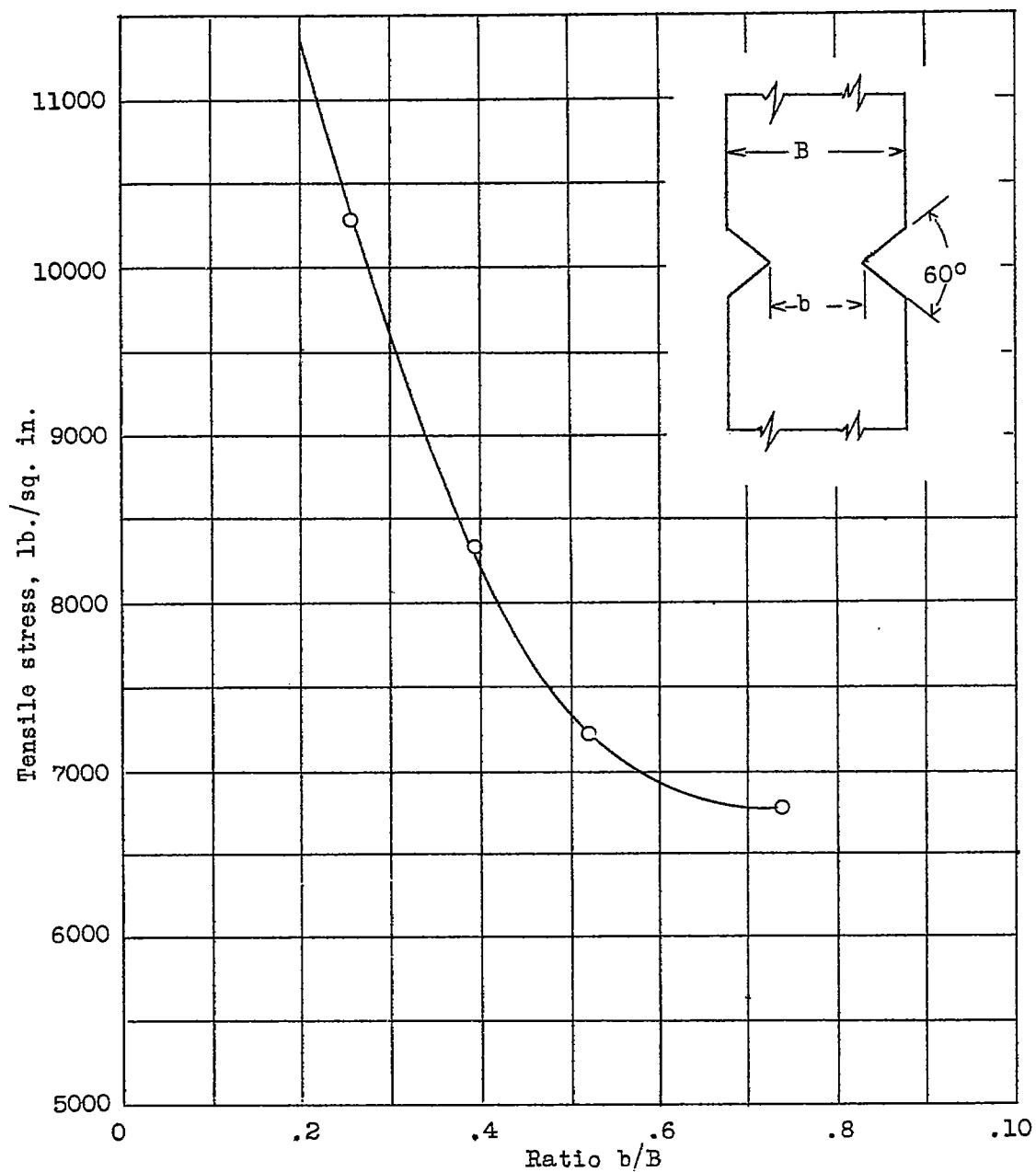
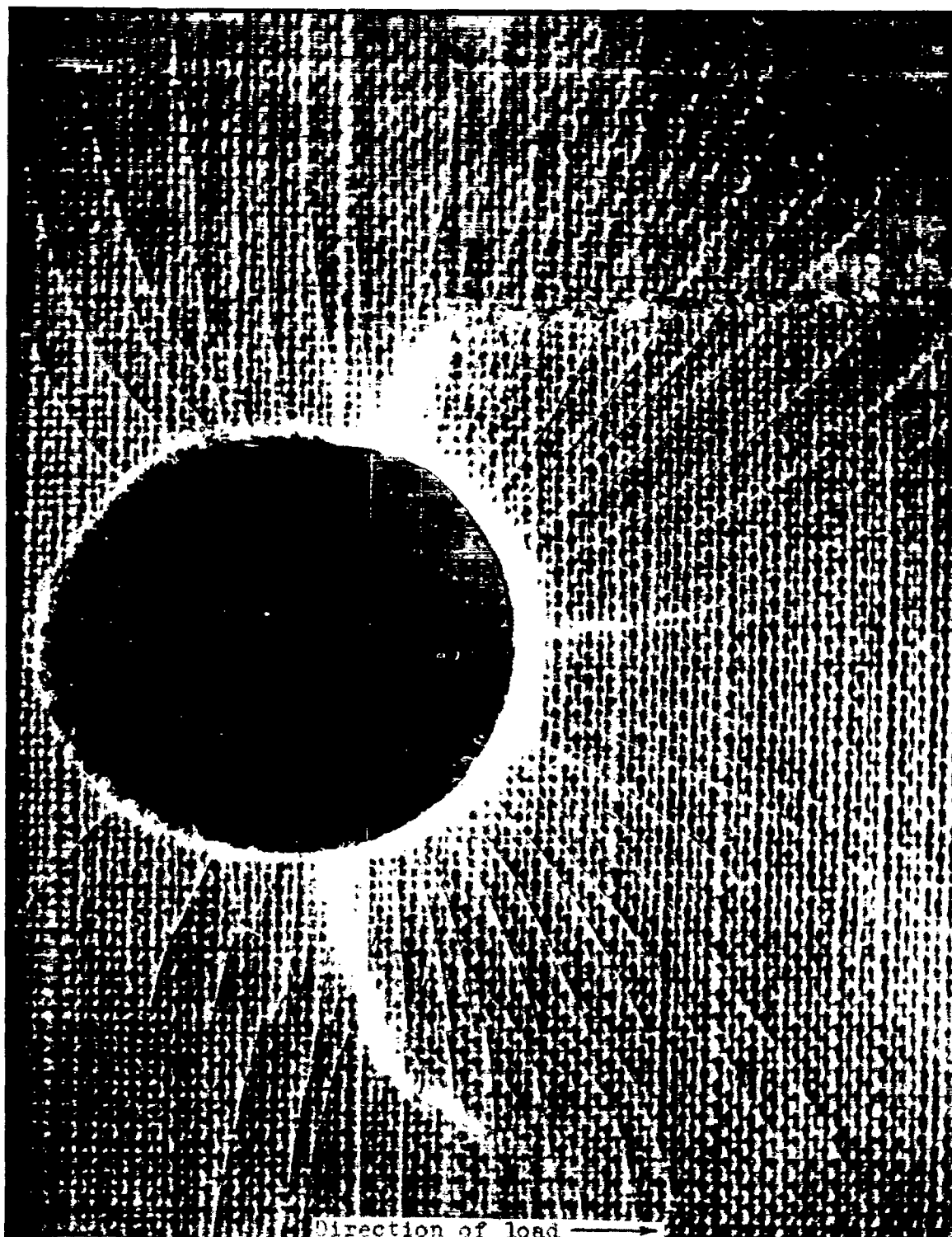Figure 11.- Notch-sensitivity tests of fabric-base synthetic resin.

Direction of load

Figure 12.- Photomicrograph of notched specimen of
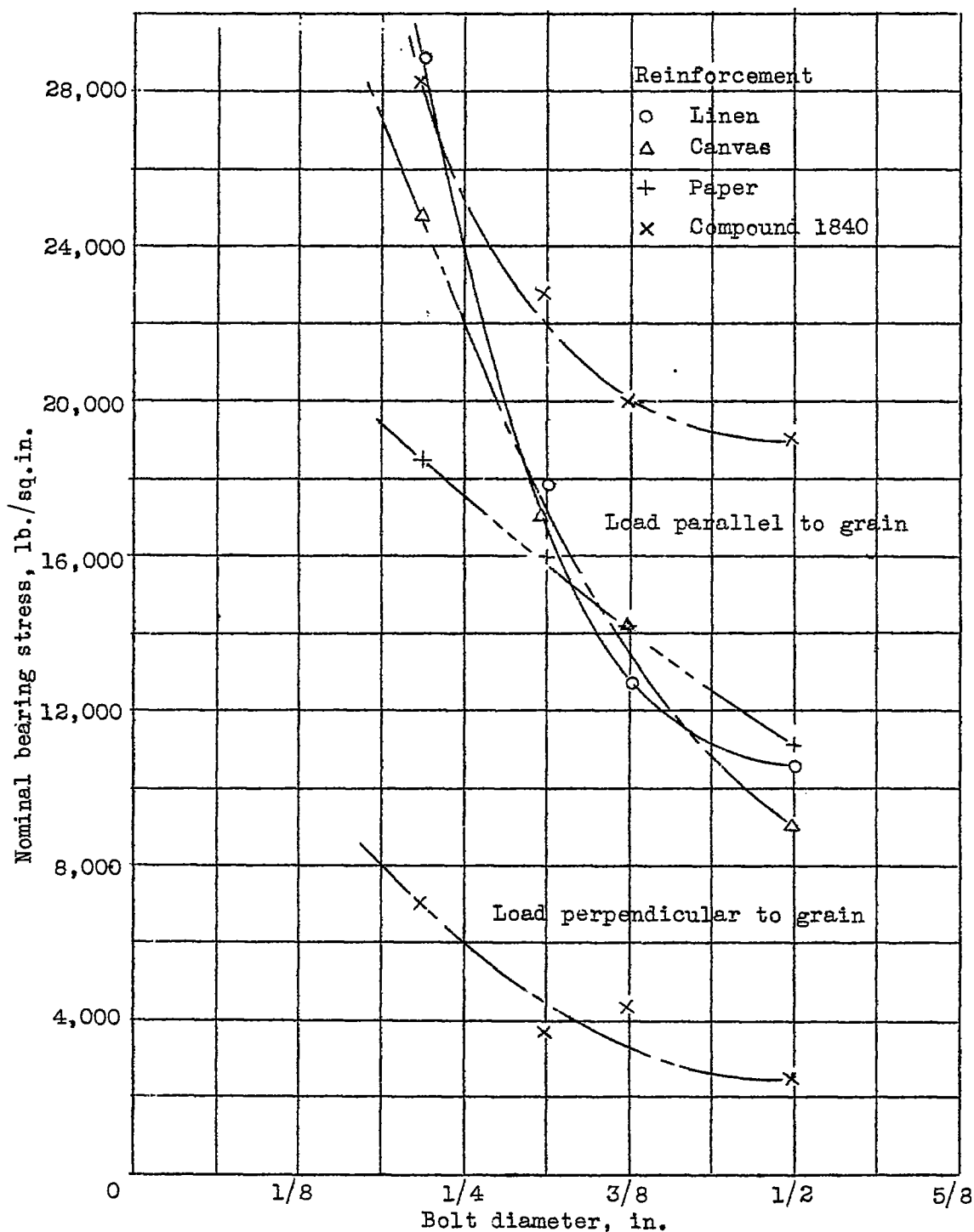synthetic resin.

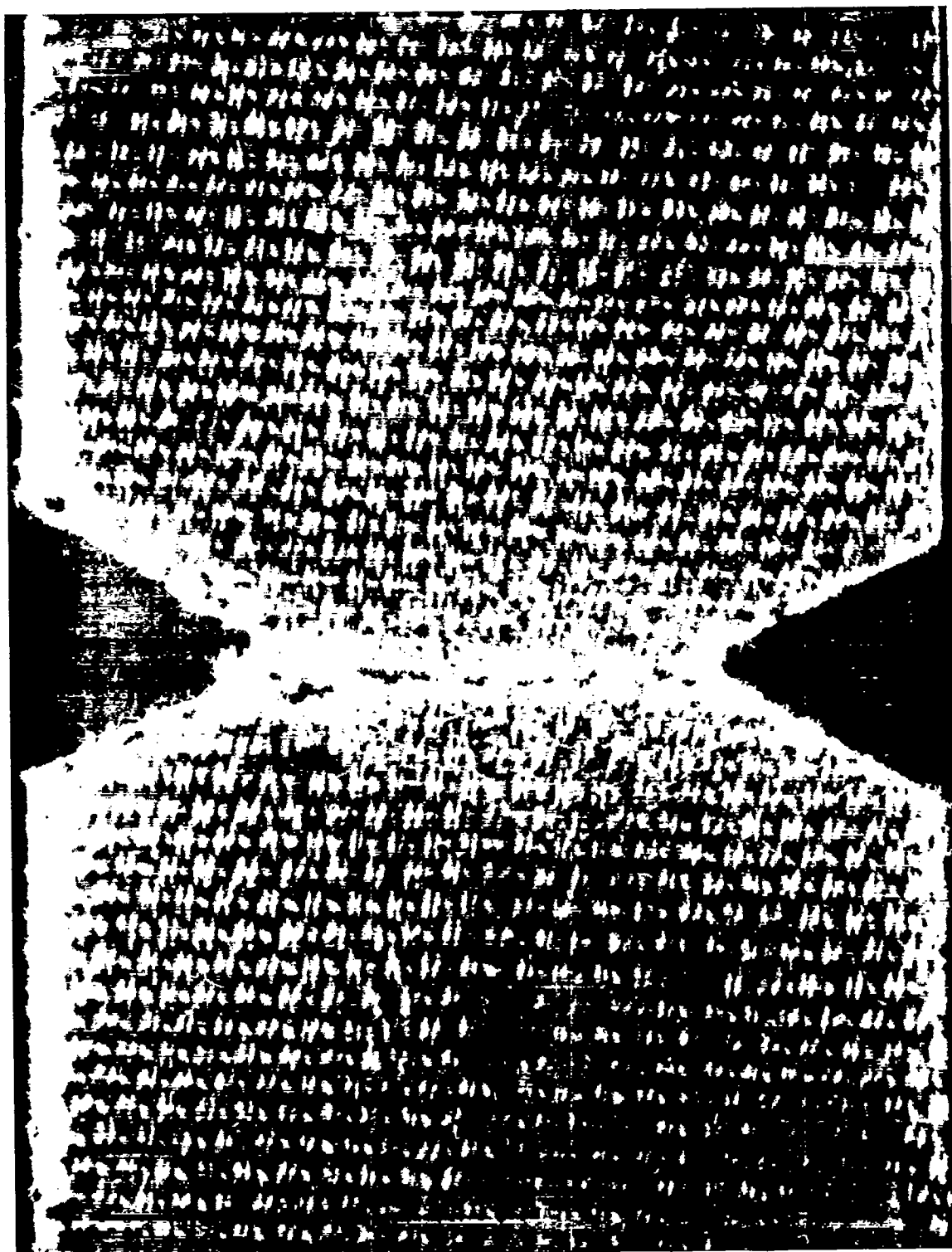Figure 13.- Variation of bearing stress with bolt diameter in bearing tests for reinforced synthetic resin.

Figure 14.- Photomicrograph of bearing bolt in synthetic
resin, fabric base.